ALMA Memo **000**, 1–3; (2009)   Printed 13 March 2009

Note #2009/1
Using Water Vapour Radiometers to Correct Total Power Observations
V0.1

B. Nikolic
Mullard Radio Astronomy Observatory, Cavendish Laboratory, Cambridge CB3 0HE, UK
email: b.nikolic@mrao.cam.ac.uk
http://www.mrao.cam.ac.uk/~bn204/

25 February 2009

1 INTRODUCTION

ALMA needs to be able to do sensitive total-power observations in order to be able to accurately image objects which are extended compared to the primary beam of the antennas. As discussed by Wright (2000), one of the primary limitations of total power measurements are fluctuations in the brightness of the atmosphere (the primary other limitation being fluctuations in the gain of the receiving system). It is currently envisaged that the atmospheric emission will be corrected by:

(i) Scanning the antennas quickly across the source so that pointings in directions of zero expected flux can be used to estimate and remove the atmospheric emission

(ii) Nutating the secondary mirror of the subset of 12 m antennas (planned to be four) that will have this facility to alternately observe the science target and a neighbouring direction with assumed zero astronomical signal

It is expected that these techniques will perform adequately in most situations. However other techniques have also been proposed which may be useful in more specialised situations. Lucas (2000) proposed a technique to correct the atmospheric emission though the frequency dependence of the emission within an astronomical band. Lucas (2000) also mentions the possibility of using the 183 GHz Water-Vapour Radiometers (WVRs) to correct for the emission.

A correction based on the WVRs would largely remove the noise due to atmospheric emission, but would also add thermal-like noise due to the noise within the radiometer itself. In this note I calculate the expected magnitude of this added noise for the production ALMA system. I am assuming that the unfiltered output of the WVRs is used for correction. In practice, if the antenna is mapping an extended region, it would be beneficial to somewhat smooth the WVR output in time to take advantage of the high degree of correlation in variation of atmospheric properties.

2 METHOD

Correction of total power observations using water-vapour radiometer observation will reduce the noise due to the atmospheric fluctuations but it will also add noise due to the thermal noise of the water-vapour radiometer itself. The key quantity for understanding this added noise is the ratio of fluctuations at the astronomical frequencies $\delta T_{\rm B}(\nu')$ as compared to the fluctuation seen within a radiometer channel at frequency ν, i.e., $\delta T_{\rm B}(\nu)$:

$$\Delta(\nu', \nu) = \frac{\delta T_{\rm B}(\nu')}{\delta T_{\rm B}(\nu)}. \qquad (1)$$

I start with the approximation that the only cause of *fluctuating* atmospheric emission is the fluctuation of the quantity of water vapour along the line of sight of the telescope. The cause of this fluctuation may be the wind moving a different part of the atmosphere within the beam, or it may be due to the beam itself moving, i.e., due to the telescope slewing. In both of these cases it is expected that the majority of the power of fluctuations is at the longest timescales (i.e., lowest temporal frequencies).

The next step is to construct a model that connect the quantity of water vapour with the brightness of the sky as a function of frequency. I make the approximation that all of the sky opacity is due to water vapour and that all of the water vapour is concentrated in a thin layer at a single pressure and temperature. The opacity due to water vapour is assumed to be the sum of contributions of the lines listed in the HITRAN catalogue (Rothman et al. 2005) and a continuum which we take to be as presented by Paine (2004). The sky brightness can then be computed in a straightforward way and I calculate the differential of sky brightness with respect to the water vapour column, $\frac{{\rm d}T_{\rm B}(\nu)}{{\rm d}c}$, using the finite difference method. Finally we need to average the computed differentials over some finite bandwidth which I do using the five-point Gauss-Legendre Quadrature (e.g., Abramowitz & Stegun 1964).

The above calculations are implemented in the `libair` package for consistency with other work we are doing (the package is publicly available for download at `http://www.mrao.cam.ac.uk/~bn204/alma/memo-infer.html` under the GPL license). The calculations should however also easily be repeatable in other publicly available packages such as ATM (Pardo et al. 2001) and `am` (Paine 2004).

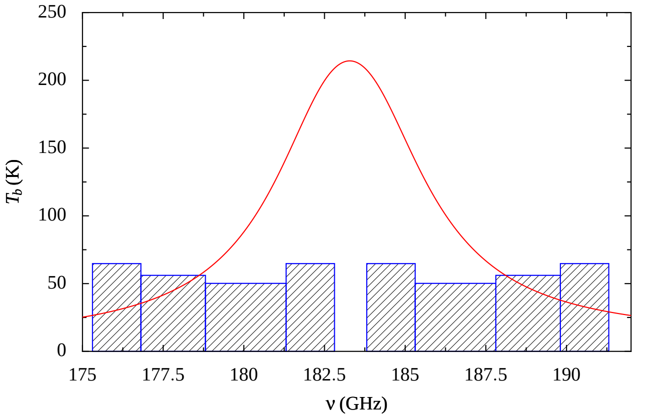


Figure 1. Filter design centres and bandwidths of the production ALMA radiometers with the 183 GHz water vapour line also shown (in red). The heights of the rectangles representing the filters are inversely proportional to the square root of bandwidth, and are therefore an indication of the relative sensitivity of the filters.

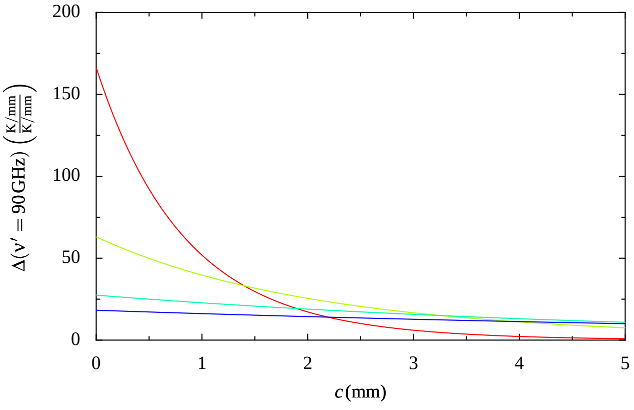
3 CORRECTING ALMA TOTAL-POWER OBSERVATIONS

Each of the 12-m ALMA antennas will have a 183 GHz water vapour radiometer fed from the centre of the focal plane of the antenna. The four channels of these radiometers are shown in Figure 1. The ALMA WVRs will have an intrinsic system noise temperature of approximately 1400 K and filter bandwidths of 1.5 to 2.5 GHz. However, in order to achieve their high stability, the WVRs need to spend about 50% of the time observing their internal calibration loads, which means that the equivalent noise of the units will be about 2000 K.

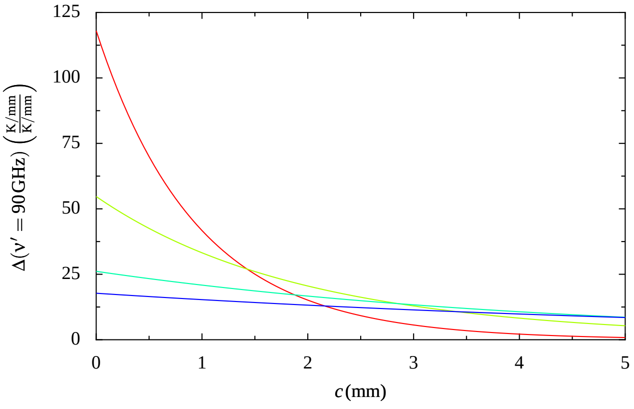
Using the method described in Section 2, it is possible to compute the parameter Δ for a range of atmospheric conditions, which we parametrise by the line-of-sight column of water vapour (c), and for a number of astronomical observing frequencies. In Figure 2a, I show the plot of Δ for astronomical frequency of 90 GHz, which is in the lowest-frequency band that ALMA will have at the time the array is commissioned. Also shown in Figure 2 is the same calculation for the OSF site where antennas and WVRs will undergo their first tests.

The median conditions at the ALMA site correspond to approximately $c = 1\,\mathrm{mm}$, i.e., to one millimetre of water vapour. Assuming astronomical observing at 90 GHz and these median conditions, the two inner channels of the radiometer will have $\Delta \sim 50$, which means that if they are used to correct total power observations, they will add noise equivalent to a temperature of $T = 2000.0\,\mathrm{K}/50 \approx 40.0\,\mathrm{K}$ and bandwidth around 2 GHz. In conditions with $1\,\mathrm{mm} < c < 2\,\mathrm{mm}$ there is always a channel with $\Delta \sim 25$ and hence we can expect to add noise with characteristic temperature of $T \approx 80\,\mathrm{K}$.

At higher astronomical observing frequencies Δ has a significantly smaller value and therefore total power correction becomes increasingly harder. For example in Figure 3 we show the computed Δ for observing frequencies of 300 and 350 GHz. It can be seen that at 300 GHz and under good conditions $c = 0.5\,\mathrm{mm}$, the inner channel will produce a $\Delta \approx 6$, meaning the equivalent noise temperature will be about 350 K. Under slightly worse conditions or higher observing frequency, the added noise will be significantly higher.



(a) AOS – Pressure = 550 mBar



(b) OSF – Pressure = 700 mBar

Figure 2. Ratio of the differentials of the sky brightens with respect to water vapour column between 90 GHz (i.e., the astronomical band) and the four channels of the production ALMA radiometers (red to blue lines corresponds to the inner to outer radiometer channels). The two plots correspond to conditions appropriate to the AOS (upper) and OSF (lower).

4 CONTAMINATION BY ASTRONOMICAL SIGNAL

One obvious complication is that the WVRs will detect any astronomical signal in the direction of the effective beam of the WVR. In some situations this will not be a significant effect because:

(i) The signal from the WVR is divided by the factor Δ before correcting the astronomical data

(ii) The WVR filter that is used will have opacity close to $\tau \sim 0.5$, therefore the astronomical signal seen by the WVR is attenuated

At 90 GHz, where the WVR correction technique is expected to work the best, the above two effects mean that typically only 2% or less of the astronomical will be lost.

Alternatively, the astronomical signal can be corrected by differencing two or more channels with weights calculated from a model of the atmosphere. This should be quite accurate but will lead to a reduction in the effective Δ, which will approximately be the difference between Δ's of the two channels; and, it will increase the effective noise, leading to more added noise to the corrected astronomical signal.

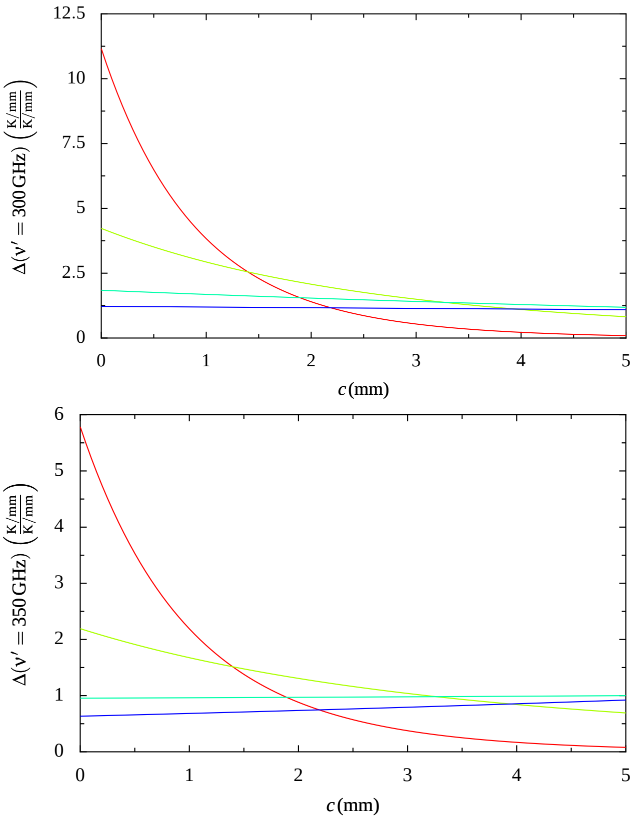


Figure 3. As Figure 2, but for frequencies of 300 (upper panel) and 350 GHz (lower panel) and only for the AOS site.

APPENDIX A: GBT

A situation in which good removal of atmospheric emission may be important is for very-wide bandwidth multi-pixel bolometer cameras which have high intrinsic sensitivity and only observe the continuum, and therefore can be limited by atmospheric fluctuations in some situations. One example of such a camera is the MUSTANG array at the Green Bank Telescope (GBT), and therefore I repeat the above calculation for conditions appropriate for the GBT.

The results, which are shown in Figure A1, show that in reasonable conditions with $c \approx 5\,\mathrm{mm}$, the ratio Δ is about 10. Therefore about 200 K of extra noise at an equivalent bandwidth of $\approx 2\,\mathrm{GHz}$ would be added by a radiometer like the ones designed for ALMA. Only the outer two channels are usable under these conditions and they have almost the same differentials of brightness with respect to water vapour column. Consequently, removal of the astronomical signal which is detected by the WVRs would be very difficult under these conditions.

REFERENCES

Abramowitz M., Stegun I. A., 1964, Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, ninth dover printing, tenth gpo printing edn. Dover, New York

Lucas R., 2000, Reducing atmospheric noise in single dish observations with alma. ALMA Memo Series 300, The ALMA Project

Paine S., 2004, The am atmospheric model. Tech. rep., SMA Technical Memo, revision 3

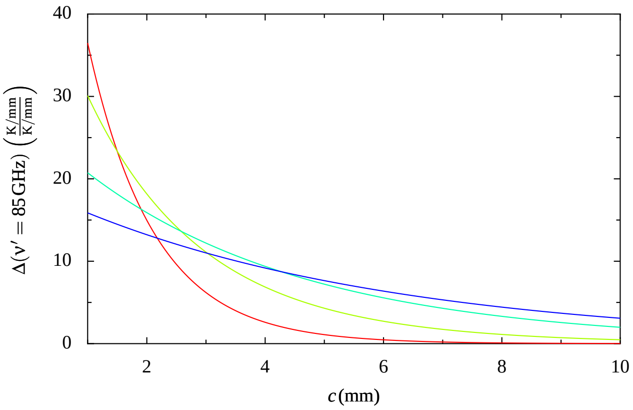


Figure A1. As Figure 2, but for the Green Bank telescope

Pardo J. R., Cernicharo J., Serabyn E., 2001, IEEE Trans. on Antennas and Propagation, 49

Rothman L., et al., 2005, JQSRT, 96

Wright M., 2000, Atmospheric noise in single dish observations. ALMA Memo Series 289, The ALMA Project